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EXTRAGALACTIC RADIO SOURCES: RAPID VARIABILITY AT 90
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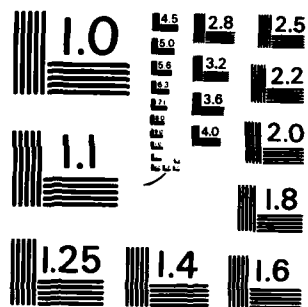
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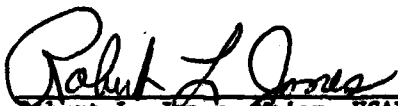
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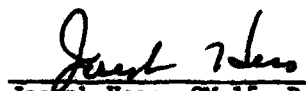
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PREFACE

We thank L. J. Rickard and J. M. van der Hulst for the OV-236 and 3C 446 measurements of 9 and 10 December 1978; M. F. Aller for making the Michigan data available in advance of publication; Don Cardarella, Dave Meyers, Werner Scherlach, Cal Sparks, and John Weaver for observing assistance at the 11-m telescope; and T. W. Jones for clarifying discussions.

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I. INTRODUCTION

Many of the important physical parameters describing compact extragalactic radio sources, such as the relativistic electron energy density; the energy content in radiation, particles, and magnetic fields; and the ratio of magnetic to electron energy, depend directly on the size of the source. Thus, a measurement of source size can determine the energetics of the source and constrain models of energy generation. Source size can be inferred from the properties of the spectrum or can be calculated from an angular size from VLBI data and a redshift-determined distance.

Another way to estimate the linear size of a source component is to observe the minimum time scale of variability. Because the effective radiating size of a compact source is, according to many models,¹⁻⁴ a function of the observing wavelength, the variability time scale should also be a function of wavelength. Variations of compact extragalactic sources are well established at millimeter and centimeter wavelengths on time scales of months and weeks and, in a few sources, on time scales of 1 to 3 days; evidence for variations over a period of hours is more limited. See the appendix.

Our objective here has been to place lower bounds on the rapidity of radio variations. We have searched for hourly and daily variability at 3.3 mm (90 GHz). We chose this short wavelength because the time scale of variations often decreases as the wavelength decreases.⁵

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II. OBSERVING PROCEDURES

Twenty-seven sources were observed for variability over the 7-day period 1-8 December 1978; these and six more sources were observed over the 5-day period 2-7 July 1979. With a few exceptions, sources fainter than 1.6 Jansky (Jy) were observed only once a day and thus were not candidates for detecting hourly variability. The (18) stronger sources were placed in groups of three and four by proximity on the sky and observed in "round robin" fashion from rising to setting. Thus, variations in the system or the atmosphere should affect all sources in a group, and should not be mistaken for real variations in a source. The selection of sources and detailed observing procedures are described in a previous paper.⁶ Observations were made with the NRAO* 11-m telescope at Kitt Peak.

Table I lists the sources observed for variability together with their average flux density, the number of days each was observed, and the total number of observations made during each observing period. The error quoted is the standard error of a single observation derived from the statistics of the set of individual measurements over the observing period. To this amount should be added (quadratically) an error of about 10% to account for uncorrected variations in the pointing and in the antenna and receiver gains, and uncertainties in atmospheric attenuation corrections. The resulting combined error is, for nonvarying sources, the upper limit of variability; for variable sources it is approximately the range of variation.

The time history of all sources was examined by eye. No source was taken to be variable if merely one measurement was divergent nor if a suggested variation vanished upon the reversal of the order of any pair of measurements. The set of time scales of variability to which our procedures are sensitive depends on the declination of the source and (somewhat) on its strength. For equatorial sources of a few Janskys, we cannot detect

*The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

Table I. 90-GHz Flux Densities (Jy) of Sources Observed for Daily and Hourly Variability

Source		July 1979				December 1978			
		S_{90}	σ^a	Days	n^b	S_{90}	σ^a	Days	n^b
0007+10	III Zw 2	1.6 ± 0.1		5	11	2.6 ± 0.4		5	19
0048-09		0.8 ± 0.1		5	7	1.2 ± 0.3		4	5
0133+47	DA 55	2.1 ± 0.2		5	15	2.1 ± 0.3		7	12
0235+16		1.6 ± 0.1		4	8	2.4 ± 0.2		6	8
0306+10	OE 110	1.1 ± 0.2		4	7	1.1 ± 0.3		5	6
0316+41	3C 84	$44. \pm 1.$		6	19	$41. \pm 3.$		6	40
0355+37	4C 50.11	5.8 ± 0.1		4	14	5.0 ± 0.8		5	23
0415+37	3C 111	2.2 ± 0.1		5	16	1.5 ± 0.5		6	23
0420-01		4.4 ± 0.7		3	8	4.3 ± 0.5		5	15
0422+00		1.2 ± 0.2		3	7	2.8 ± 0.4		5	15
0430+05	3C 120	1.2 ± 0.3		4	9	1.9 ± 0.5		5	17
0735+17		1.2 ± 0.4		4	7	1.6 ± 0.2		5	9
0851+20	OJ 287	3.2 ± 0.2		4	10	3.7 ± 0.5		5	34
1219+29	W Com	1.3 ± 0.3		4	5	1.5 ± 0.4		5	8
1226+02	3C 273	14.8 ± 0.9		5	20	12.9 ± 1.0		5	36
1228+12	Virgo A	6.6 ± 0.5		5	11	7.1 ± 1.0		4	14
1253-05	3C 279	6.4 ± 0.4		5	11	7.1 ± 0.8		5	30
1308+32		1.7 ± 0.1		5	6				
1335-12		7.5 ± 0.6		5	11	4.4 ± 0.6		5	28
1418+54	OQ 530	3.0 ± 0.3		5	5				
1510-08		2.4 ± 0.4		5	5				
1514-24	AP Lib	1.8 ± 0.1		5	7	1.1 ± 0.4		4	5
1641+39	3C 345	6.9 ± 0.6		4	9	7.2 ± 0.9		5	15
1730-13		4.1 ± 0.3		5	6				
1739+52		1.3 ± 0.2		5	10	1.5 ± 0.3		7	7
1749+09		3.2 ± 0.4		5	5	6.7 ± 0.8		5	14
1921-29	OV-236	9.8 ± 0.5		5	10	4.4 ± 2.2		6	21
2037+51	3C 418	2.7 ± 0.3		6	14	3.4 ± 0.6		6	22
2200+42	BL Lac	1.8 ± 0.1		5	14	1.4 ± 0.4		6	13
2201+31	4C 31.63	1.9 ± 0.1		5	13	2.7 ± 0.6		5	11
2216-03		2.1 ± 0.2		5	9				
2223-05	3C 446	5.6 ± 0.4		5	11	3.9 ± 0.5		5	20
2251+15	3C 454.3	3.9 ± 0.3		5	11	4.5 ± 0.4		5	19

^a Standard error of a single observation.

^b Total number of observations.

variations in less than two hours or more than 10 days, quasiperiodic changes in multiples of 24 hours, and certain variations in 8-14 hr if in phase with the rising and setting of the source.

III. RESULTS

Except for OV-236 (1921-29) in December 1978, none of the sources exhibited statistically significant variations within either observing period. Figure 1 shows the time history of four well studied, but otherwise typical nonvarying sources during the July 1979 period. The error bars shown are 2σ in total length and are derived from the scatter of individual beam-switched integrations of 30-s duration within the observation. Of all the "nonvarying" sources, OJ 287 comes closest to showing variability; all other sources behaved more like II Zw 2 and BL Lac.

The flux density of OV-236 decreased from an average value of 6.4 ± 0.9 Jy during the interval 1-4 December 1978 to 2.4 ± 0.9 Jy on 7 December, then rose to 6.5 ± 0.3 Jy on 9 and 10 December. Its behavior is shown in Fig. 2, together with that of 3C 446, which is near OV-236 on the sky. That the entire antenna and receiver system was functioning properly throughout the run is indicated by the constancy of 3C 446. Observations of these two sources and of the calibration source DR 21 were interspersed during the measurements on 7/8 December. (Observations of OV-236 and 3C 446 on 9 and 10 December were kindly made by L. J. Rickard and J. M. van der Hulst.)

A real drop in flux density by a factor of 2.7 within a few days would be quite remarkable. We have therefore investigated as many alternative explanations for this variation as we could imagine. However, any such explanation must account for the constancy of 3C 446 during this time. Since 3C 446 trails OV-236 by 2 hr in R.A. (and is 25° north), any change in the system (such as pointing) would have to have been confined to declinations well to the south of 3C 446 and/or to have moved across the sky with OV-236 so as not to affect 3C 446. Moreover, any such anomaly would have to have reversed itself exactly by the time the flux density of OV-236 was measured two days later at its pre-drop value.

Table II is a journal of measurements of OV-236. Observations made close together have been grouped, and σ is the error of a single observation (the

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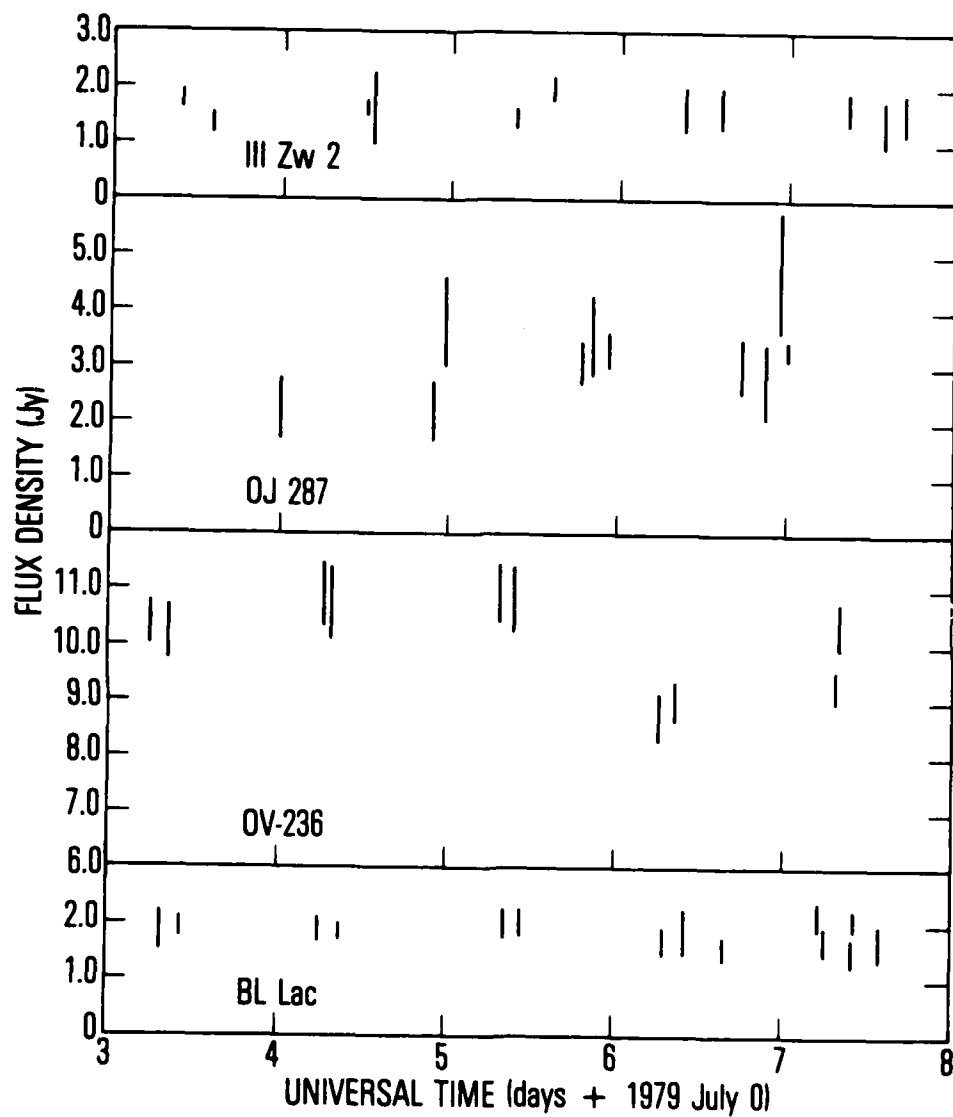


Fig. 1. 90-GHz Flux Density of Four Typical Nonvarying Sources vs. Time, Over the Period 2-7 July 1979

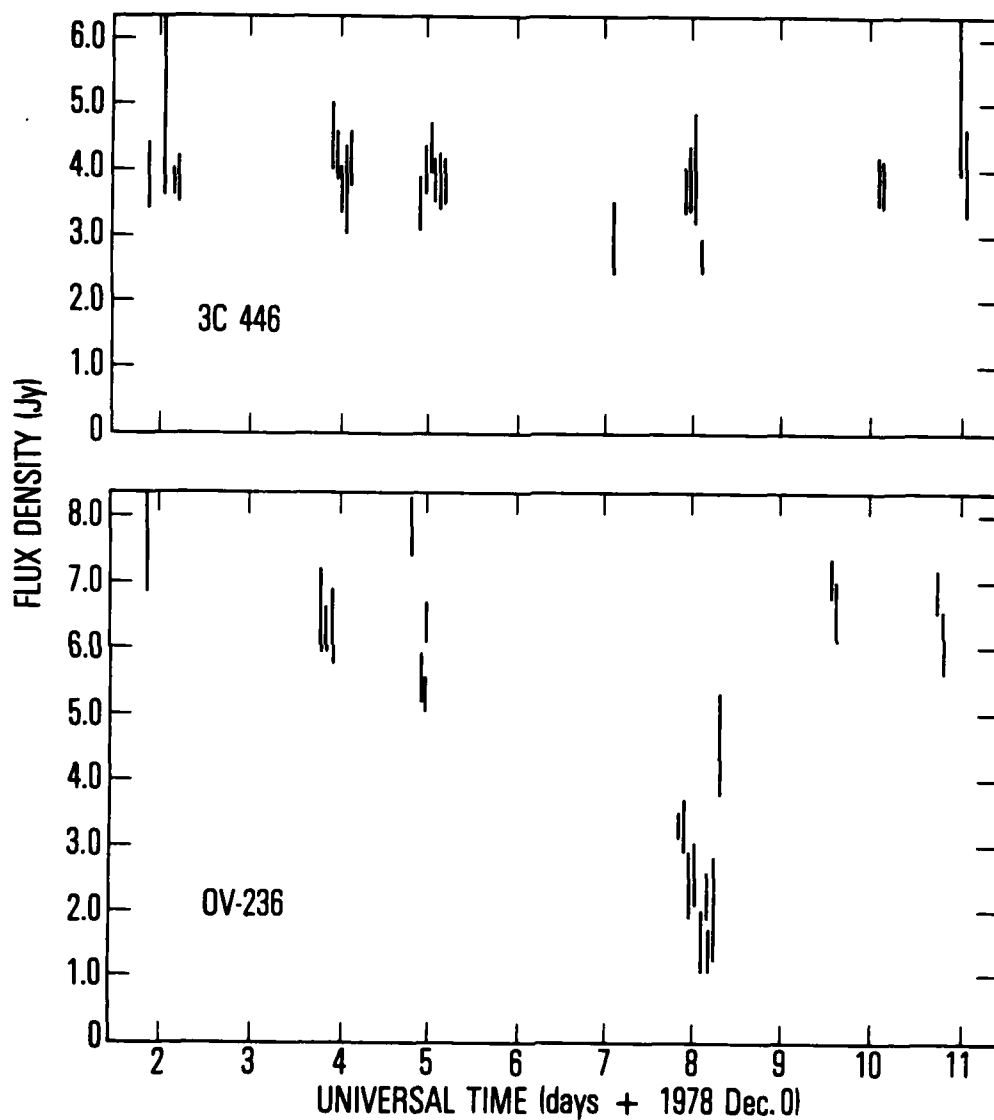


Fig. 2. 90-GHz Flux Density of 3C 446 and OV-236 vs. Time, Over the Period 1-10 December 1978. For clarity in display of the OV-236 drop, the time scale around 0^h UT 8 December has been expanded by a factor of 4.

Table II. Journal of 90-GHz Observations of OV-236 in
December 1978

Universal Time	Air mass	τ	Ambient temperature	S_{90}	σ^a	n^b
1978 Dec 1 ^d 20 ^h 30 ^m	2.41	0.085	+13.9°C	7.53 ± 0.68		1
3 21 30	2.15	0.053	+3.5	6.35 ± 0.17		3
4 20 25	2.37	0.085	+9.4	7.73 ± 0.45		1
4 22 50	2.19	0.089	+9.4	5.70 ± 0.60		3
7 22 53	2.1-2.3	0.060	-3.0	2.83 ± 0.56		4
8 0 26	2.9-3.8	0.060	-4.4	2.30 ± 1.28		5
9 22 39	2.20	0.070	+3.9	6.78 ± 0.29		2
10 21 36	2.08	0.070	+8.0	6.53 ± 0.49		2

^a Standard error of a single observation (except for $n = 1$, σ is the rms error of 11 30-s integrations which comprise the observation).

^b Number of 5-min observations made at each time.

rms deviation of the observations within a group). For groups of one, σ is the rms deviation of 11 30-s integrations comprising the observation.

A. POINTING

Known pointing corrections are automatically applied to the telescope's position every 20 s during tracking. Second-order corrections are derived from accurate position measurements of the planets and other strong sources at many places in the sky and entered as offsets to the commanded position of the telescope. They change and must be reentered as a source is followed across the sky. A third-order correction in azimuth is required as a function of ambient temperature; it amounts to about 1 arcsec/ $^{\circ}$ C. Our December observing period immediately followed a day dedicated to re-determining the pointing corrections, which we inherited^{*} and augmented. By 7 December we had obtained a dense grid of 120 second-order corrections as a function of azimuth and elevation, as well as their approximate dependence on temperature. Pointing corrections for the part of the sky through which OV-236 passed were derived from observations of Mars, whose path was only 5 deg north of that of OV-236. We see from Table II, however, that the observations on 7/8 December were made at an ambient temperature 7 $^{\circ}$ C below those of 3 December and 13 $^{\circ}$ C below those of 4 December. If we assume a maximum error in our pointing corrections of $\epsilon = 13$ arcsec owing to this temperature effect, the diminution of the flux density expected for a Gaussian beam profile of half-power width HPBW = 76" is $1 - \exp\{-0.693[\epsilon/1/2 \text{ (HPBW)}]^2\}$ or $\sim 8\%$, not nearly enough to account for the observed signal drop. A pointing error of 46" would be required to account for the drop; in our experience with the 11-m antenna we have never measured so large a sudden pointing change.

B. ANTENNA GAIN VARIATIONS

Sixty-four measurements of the brightness temperatures of Jupiter, Saturn, and Venus were made with the 5-point-grid procedure during the December 1978 observing period and analyzed for variations as a function of

^{*}Ulich, B. L., private communication.

zenith distance and ambient temperature. No variation with zenith distance was found. However, there is a strong dependence of the brightness temperatures (normalized to the average brightness temperature for each planet) on ambient temperature — see Fig. 3. The regression line has a slope of $+1.3\%/^{\circ}\text{C}$, and the correlation coefficient is 0.74. Assuming this trend represents a variation of antenna aperture efficiency with temperature, and that it affects point sources and planets similarly, then the change of $\sim 10^{\circ}\text{C}$ between 4 or 9 December and 7/8 December could lead to a diminution of the flux density of OV-236 by at most 13%. The mechanism by which the temperature affects the antenna aperture efficiency is unknown; astigmatism is apparently not the agent, since we found no variation of beamwidth with ambient temperature.

C. EXTINCTION

Because of its large negative declination, OV-236 was always observed through at least 2 air masses. However, the opacity of the atmosphere was uniformly low throughout the observing period. The zenith optical depths τ are given in Table II. A 100% error in determining τ produces an error of only $\sim 20\%$ in the flux densities.

D. SKY CONDITIONS

Sky conditions were monitored by frequent visual inspection throughout both observing runs; the sky was completely clear most of the time. Since it was obvious after the first 5-min observation of OV-236 on 7/8 December that a significant drop had occurred, the sky conditions were noted for every subsequent OV-236 observation. The sky was generally clear, but there were scattered alto-stratus clouds present. The analog records of the receiver's switched and total power outputs readily indicated when a cloud was actually in the antenna beam; two OV-236 observations were rejected. Our conclusion from visual inspection that there were no atmospheric irregularities in the antenna beam during the remaining nine observations was confirmed by the smoothness of these analog records.

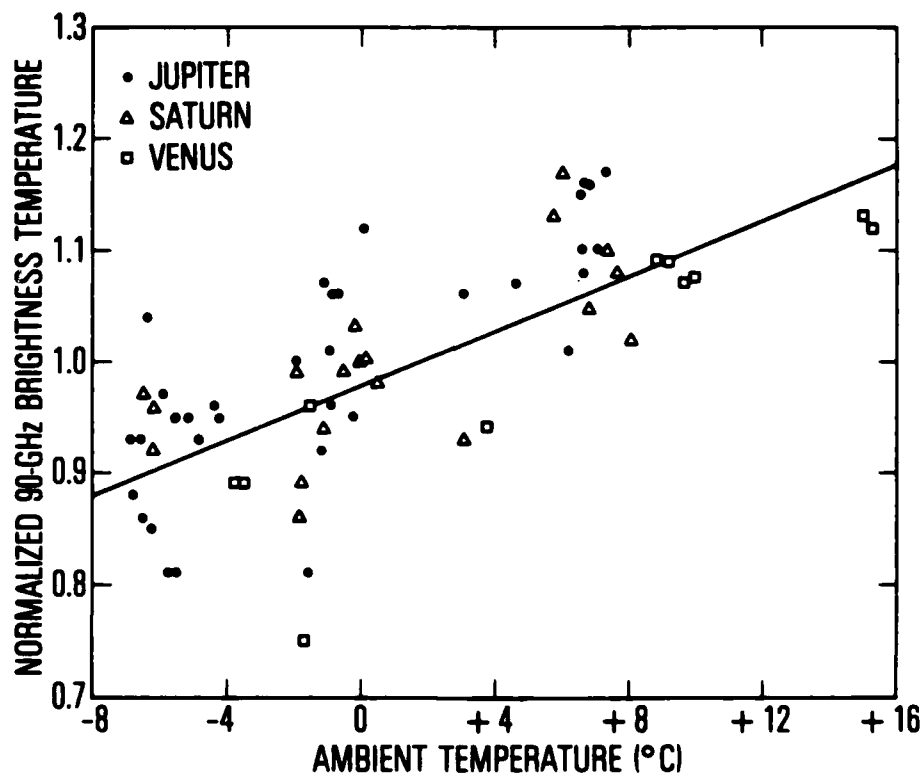


Fig. 3. 90-GHz Brightness Temperatures of Jupiter, Saturn, and Venus Measured with the NRAO 11-m Radio Telescope Over the Period 1-8 December 1978 and Normalized to the Average Brightness Temperature of Each Planet vs. the Ambient Temperature at the Time of Measurement. The slope of the regression line is $+1.3\%/^{\circ}\text{C}$; the correlation coefficient is 0.74.

E. SUN IN SIDELOBES

The Sun was ≈ 22 deg away from OV-236. Five of the nine observations on 7/8 December were made after sunset. There was no significant change in flux density after sunset.

In summary, no anomalous behavior of the system or atmosphere was noticed during any of the observations of OV-236 reported here. Furthermore, the other sources observed at the same time (3C 446, 3C 418, DR 21) remained constant within the observational errors of $\approx 20\%$. We conclude that the large drop in OV-236's flux density on 7/8 December was intrinsic to the source.

IV. DISCUSSION

A. NONVARYING SOURCES

None of the variable sources we observed were undergoing outbursts during our measurements. Our remarks therefore apply only to the "quiescent" phases. Except for OV-236, we observed no variability time scale t shorter than ~ 10 days. (The variability of an object varying on a time scale of about 10 days or less would have been detected during a 5- to 7-day observing run.) In the absence of relativistic motions within these sources, this limit implies 3-mm regions larger than $R = ct/(1+z)$, or 2×10^{16} cm for a redshift z less than 0.3.

The corresponding angular sizes are greater than $\theta(3 \text{ mm}) = tH(1+z)/z$, or about 3×10^{-6} arcsec for a Hubble constant $H = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The observed brightness temperatures of compact synchrotron sources fall in the range $\sim 10^{11}$ to $\sim 10^{12}$ K (Ref. 7). This small range is a result of the insensitivity of angular sizes (thus T_B) to such important physical parameters as the magnetic and electron energy densities.⁸ The upper limit is also set by inverse Compton cooling.⁷ Regardless of the explanation, this limited range of brightness temperatures leads to the result that the apparent angular size of the source scales directly with the observing wavelength throughout the region where the spectrum is flat. Thus, the absence of 3-mm variability on a time scale of ~ 10 days means that for a wavelength of, for example, 6 cm (a typical VLBI wavelength), the angular size of the 6-cm emitting region, $\theta(6 \text{ cm})$, is $\gtrsim 6 \times 10^{-5}$ arcsec. This value is just below the limit of VLBI resolution at 6 cm of $\sim 2 \times 10^{-4}$ arcsec.⁹ Unresolved sources with variability time scales $\gtrsim 10$ days therefore cannot be much smaller than those which have been resolved.

These sizes are also consistent with the shape of the spectrum, particularly with the wavelength at which these flat spectra begin to turn down. This turndown point, separating radiation from the optically thick and optically thin regions, occurs at a wavelength^{10,11}

$$\lambda(\text{mm}) \approx 0.1 \left(\frac{t}{\text{days}} \right) \left(\frac{0.01}{z} \right) \left(\frac{\text{Jy}}{S} \right)^{1/2}$$

Thus for a typical source flux density of ~ 1 Jy and a z value of, say, 0.03, the turndown would be at ~ 1 mm for a source varying on a 1-month time scale and at ~ 30 μm for a source with a 1-day time scale. Since, as a class, our sample of compact sources varies with time scales of months, but not days, we expect the turndown to occur shortward of ~ 1 cm; that is, we expect spectral indices around zero between 6 cm and 3 mm. The results of Owen et al.¹² and Landau et al.⁶ demonstrate that this is so.

B. OV-236

The Ohio radio source OV-236 is identified with an optically variable, red, emission-line object with a redshift of 0.35.^{13,14} Astrometry of ESO films shows the identification of Radovich and Kraus¹⁵ to be in error; the VLBI position of Gubbay¹⁶ or the VLA position $19^{\text{h}}21^{\text{m}}42^{\text{s}}.18$, $-29^{\circ}20'24.9''$ is to be preferred.

OV-236 was noted to be variable at 2.8 cm by Kraus and Andrew¹⁷ and at both 9.5 and 3.3 mm by Conklin et al.¹⁸ At 3.3 mm the flux density dropped from 3.8 ± 1.3 to 0.9 ± 1.1 Jy between 30 June and 5 July 1970, while at 9.5 mm it decreased $\sim 25\%$ (from 6.5 ± 0.35 to 4.9 ± 0.26 Jy) between 1 and 4 July 1970. Further measurements at 3.3 mm showed flux densities of 2.7 in September 1974.^{**} Monitoring at 2.8 and 4.5 cm^{19,20} has shown fluctuations of about 10% from month to month and a 20% decrease from 1970 to 1976. From 1976 to early 1979 the millimeter and centimeter flux densities gradually increased; the December 1978 3-mm drop we report here occurred a few months prior to a pronounced acceleration in this increase.^{21,22}

[We note that sharp, large drops on time scales of days have now been observed in OV-236, OJ 287 (Refs. 5 and 23), and 3C 273 (Ref. 5). It is our impression that equally sharp and large rises have not been observed.]

*Fomalont, E. B. and Perley, R.A., Unpublished VLA Calibration Manual.

**Conklin, E. K., private communication.

The spectra in 1970 (Ref. 18) and December 1978 (Ref. 21) are both rising between 10 and 2 cm with a spectral index $\alpha = -0.4(S \sim \nu^{-\alpha})$. The 3-mm flux densities, however, are always lower than the 2-cm values, implying a maximum in the spectrum near 1 cm.

Such a rapid, large-amplitude variation at 3 mm as reported here for OV-236 and as reported for OJ 287 and 3C 273 (see the appendix) cannot be explained as the expected behavior of a nonrelativistically evolving, incoherent, synchrotron source. If these results are confirmed, a different model, perhaps one exhibiting relativistic expansion, one in which the radiating electrons have much shorter lifetimes, or one involving an orbiting pair of source components will be needed to explain the rapidly variable component of the flux densities.

V. SUMMARY

Thirty-three extragalactic variable radio sources have been observed at 90 GHz (3.3 mm) over two several-day-long periods in a search for daily and hourly variations. OV-236 (1921-29) showed a decrease in flux density by a factor of 2.7 over a three-day interval, recovering its previous flux density two days later. (OV-236 began a dramatic outburst a few months later.) The other sources exhibited no significant variations $\geq 20\%$. A summary of previous radio observations of rapid variability is contained in the appendix.

APPENDIX

PREVIOUS RADIO OBSERVATIONS OF RAPID VARIABILITY

Variations of compact extragalactic radio sources at millimeter and centimeter wavelengths on time scales of months are well known: for example, see Refs. 6, 24, and 25 for 3.3 mm; Ref. 26 for 9 mm; Ref. 20 for 2.8 and 4.5 cm; and Ref. 27 for 3.3 and 11.1 cm.

Several reports exist of interday variability at radio wavelengths. Wills²⁸ observed interday variations of 2-4% in the 11.1-cm emission from 0106 + 01, 0336 - 01 (CTA 26), 0440 - 00 (NRAO 190), and 1510 - 08 during 1969. During two 26-hr intervals in 1969 she found no evidence in the 11.1-cm emission from several sources for intraday variability larger than the noise level of $\sim 2\%$. The data of Kinman and Conklin²³ suggest a drop of $\sim 40\%$ and of less than 4 days' duration in OJ 287's 3.5-mm emission in May 1971; there was some suggestion of a correlation with optical variations. Andrew et al.²⁹ also observed OJ 287 in the spring of 1971; they found variations in the 4.5-cm signal of $\sim \pm 8\%$ on a time scale as short as 1 day. Harvey et al.³⁰ observed 19 sources at 2.8 cm daily for 20 days in October/November 1971; BL Lac exhibited a rise of $\sim 6\%$ in one day followed by a decline of $\sim 12\%$ in one day; and OJ 287 exhibited an outburst of $\sim 5\%$ lasting ~ 5 days. The 17 other sources showed no variations. Gorshkov et al.³¹ reported a decrease of $\sim 20\%$ in the 3.5-cm flux density of 3C 273 from 23 to 27 May 1969, but the published observational data are limited.

Epstein et al.³² made coordinated multifrequency searches for intraday variability in 3C 120, BL Lac, and OJ 287. Their 3.5-mm OJ 287 data reveal a change of $\sim 40\%$ in ~ 2 hr on 18 February 1972 and suggest smaller changes with the same time scale on three adjoining days. (The 2.2- μ m OJ 287 data show an increase of $\sim 25\%$ in ~ 1 hr on 17 February 1972; the increase was not correlated with the suggested 3.5-mm change on that night.) There were suggestions of 3.5-mm interday variability of $\sim 20\%$ for OJ 287 and BL Lac, but not 3C 120. A subsequent coordinated search of these same three sources during

the winter of 1972/73 resulted only in upper limits of $\sim 25\%$ for 3.5-mm intraday variations and $\sim 20\%$ for interday variations.* During this same coordinated search, Kikuchi et al.³³ observed a 20% decrease in the 7.2-cm flux density of OJ 287 over 100 min on 8 February 1973. Huchtmeier and Wright³⁴ observed in March 1973 the 6-cm flux density of III Zw 2 rise $\sim 13\%$ in one day, then decline $\sim 20\%$ during the subsequent 5 days. Kinman et al.,³⁵ in a coordinated multifrequency study of OJ 287 in January 1972, found variations of $\sim 10\%$ on time scales of 1-3 days at 3.5, 28, 37, and 45 mm. Efanov et al.³⁶ found declines of $\sim 15\%$ and $\sim 20\%$ in the 13.5-mm flux density of 3C 273 in just ~ 4 hr on 22 and 29 March 1976, respectively; on both occasions the partial recoveries took 1 to 2 days. Kellermann³⁷ found a decline of $\sim 40\%$ in the 3.4-mm flux density of Cen A between 27 and 28 March 1974. Kaufmann et al.³⁸ observed a possible variation of $\sim 30\%$ in the 13.5-mm signal of Cen A on a time scale of about 5 days in November/December 1976. Kaufmann and Raffaelli³⁹ then observed Cen A at 7 and 14 mm daily for 46 days in July/August 1978; they found repeated 7-mm variations of amplitudes up to $\sim \pm 20\%$ on time scales of 1 or 2 days. Indicated variations at 14 mm were much smaller and less certain. Epstein et al.⁵ observed drops of $\sim 50\%$ in the 3-mm flux density of 3C 273 on a time scale of 1 to 2 days in July and November 1969 and a drop by a factor of ~ 2 in OJ 287 in March 1972, on a time scale of ~ 2 days.

Interday variations have been seen in the optical domain; e.g., see DuPuy et al.⁴⁰ for BL Lac, Kinman et al.³⁵ for OJ 287, and Miller⁴¹ for 1418 + 54. Racine⁴² has found BL Lac to vary by 0.1 mag in hours.

*Epstein, E. E., unpublished.

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